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Reservoir Characterization from Exploration Well Completion Tests in the Fiale Caldera, Djibouti

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ABSTRACT

Completion testing consisting of injection and pressure fall-off tests and pressure, temperature, and spinner surveys preformed in two deep exploration wells during and after drilling are used to characterize the shallow and deep geothermal reservoirs in the Fiale caldera, Djibouti. Shallow injection testing conducted during temporary drilling stoppages in wells Fiale-2 and Fiale-3 indicated the presence of a potentially commercial grade shallow reservoir ultimately placed behind casing in these exploration wells. Deep injection testing conducted in Fiale-2 and Fiale-3 indicates the possible presence of a high temperature commercially viable deep resource, prior to the completion of more costly and involved production testing activities. The data collected from these tests increases the understanding of the geothermal systems in Fiale caldera and can be used in future development of both the shallow and deep reservoirs. The testing of Fiale-2 yielded valuable information that was employed to inform the drilling location, target, and well construction of Fiale-3.

The most current conceptual model, based on well data from Fiale-1, -2, -3, and Assal-5, and surface geologic mapping, indicates that all of these wells encounter similar geologic and hydrothermal conditions both within and outside of the Fiale caldera boundaries. A shallow liquid dominated geothermal resource with measured temperatures of up to 214°C exist at depths of 500-850 m. This resource is associated with the transition from basalt to intermediate volcanics (trachyte) indicating lithological control. A temperature reversal to 70°C is inferred to be created from the flow of marine water from the Bay of Ghoubbet towards Lake Assal at depths of 850-1500 m. A deep liquid dominated resource exists below depths of >1700 m that has measured temperatures of up to 368°C. The reservoir fluid is likely concentrated seawater

and maximum temperatures and pressures are estimated to be close to, but below the critical point of seawater at the bottom of the wells.

1. Introduction

A feasibility study, including three deep exploration wells drilled within the Fiale caldera, is being conducted to assess the viability of a 50 MW geothermal power project at the Fiale caldera in the Asal rift, Djibouti. The Asal rift is a major deformational geologic structure located near the northern terminus of the East Africa Rift System. The evolution of the Asal rift has been influenced by the Red Sea, Gulf of Aden, and East Africa extensional structures and is related to the greater Afar depression with high heat flux and recent volcanism (Barberi, Ferrara, Santacroce, & Varet, 1975; Pinzuti, Mignan, & King, 2010). Numerous geologic, geophysical, and geochemical studies have identified areas of geothermal potential within the Asal rift and surface manifestations exist in several locations including fumaroles along the southern margin of Fiale caldera (Correia, 1985). The first period of regional exploration drilling lasted from 1970 to 1990 and included the drilling of six deep exploration wells, including Assal-5, which is located ~600 m west of the Fiale caldera boundary (Khaireh & Aye, 2012; Zan, Gianelli, Passerini, Troisi, & Haga, 1990). A regional map is present in Figure 1.

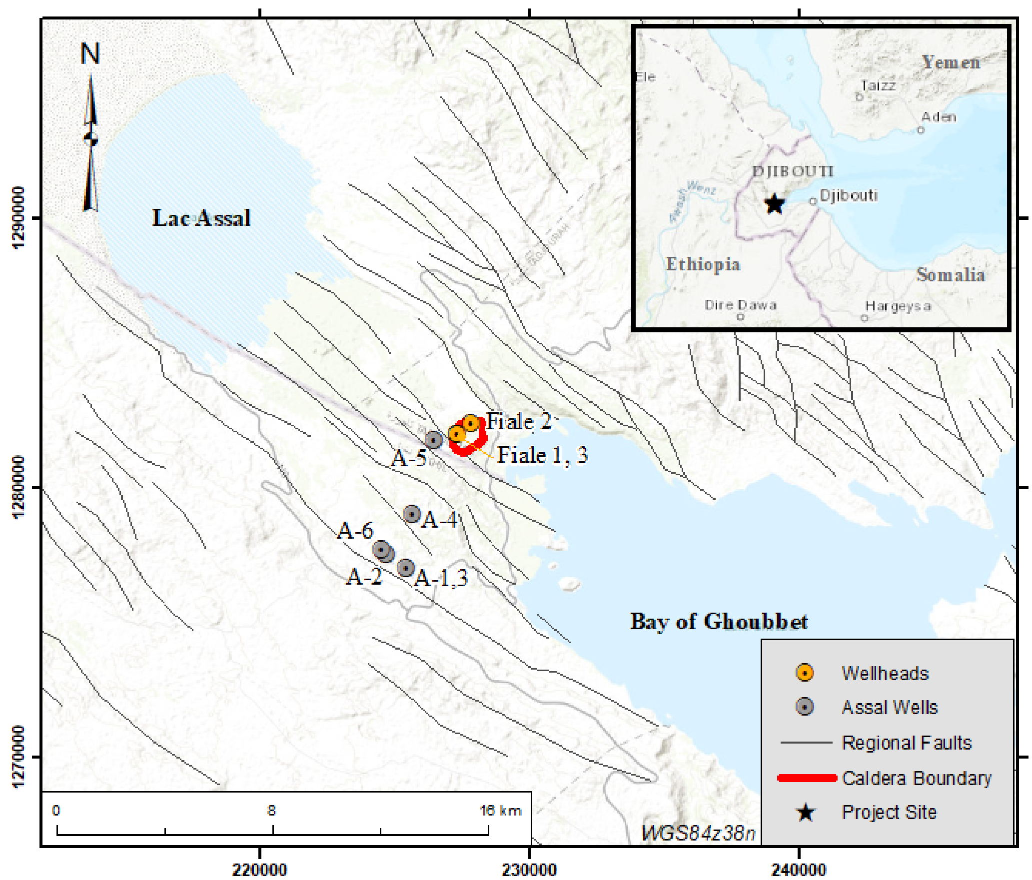

Figure 1. Regional map of project site displaying the caldera boundary, Assal wells, and Fiale wells as well as regional faults from (Le Gall, et al., 2015).

Multiple injection tests were completed in Fiale-2 and Fiale-3 in order to identify and characterize the preliminary resource parameters in the Fiale caldera such as temperature and permeability of both the shallow ~150-214 °C reservoir and deep >225 °C reservoir, prior to completing more complex and costly production testing activities. Preliminary testing consisted of cold seawater injection, dynamic pressure, temperature, and spinner (PTS) surveys, and downhole pressure monitoring during injection and pressure fall-off (PFO) after shut-in. All tests were completed while the drilling rig was on the hole and designed to minimize rig time. Shallow injection tests were performed after setting the 13 3/8" casing string, the rig had drilled ahead to an intermediate depth and the well was open to the shallow reservoir, but before it encountered the temperature reversal caused by the intermediate cold seawater intrusion. Deep injection tests were completed after drilling to the total depth and production casing had been set to seal off the shallow reservoir and intermediate cold seawater intrusion.

Multi-rate seawater injection tests were completed with ~2-hour rate periods and the stabilized downhole pressures were used to determine the injectivity. PFO was recorded for ~4 hours after the well was shut in. Static PT and dynamic PTS surveys were completed in order collect downhole pressure data, identify fluid loss and/or entry zones, and estimate the natural-state formation temperature using the Horner build-up method (Roux, Sanyal, & Brown, 1979).

2.1 Shallow Injection Tests

2.1.1 Fiale-2 Shallow Reservoir

A brief multi-rate injection and PFO test was conducted in Fiale-2 on 14 November 2018 after the well was drilled to 780 meters measured depth (mMD) and the 13 3/8" casing was set to 523 mMD. The objective of this testing was to evaluate the permeably of the shallow reservoir prior to sealing it behind 9 5/8" cemented casing. The downhole pressure data and injection rates for the shallow injection test are shown in Figure 2.

The injection rates are plotted against the stabilized downhole pressure (Figure 3); the slope of the line indicates an injectivity index (II) of 3.3 kg/s/bar. This indicates commercial grade permeability.

After the injectivity test, the well was shut-in and the pressure measured just above the 13 3/8" casing shoe (522.6mMD) for ~4 hours. For the evaluation of permeability, the pressure changes are evaluated against reduced time. The slope of the straight-line is related to the reservoir permeability.

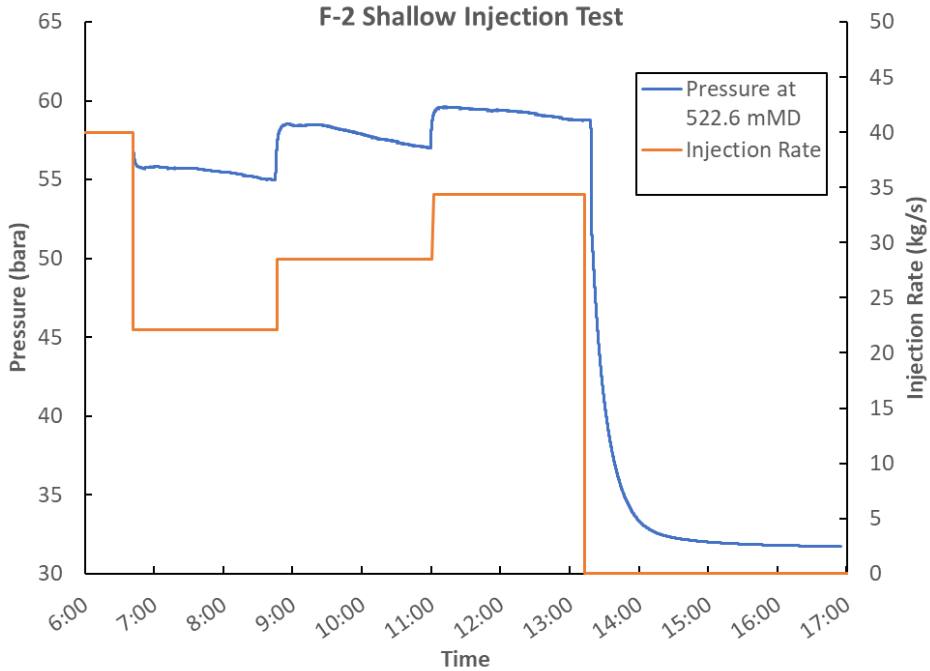

Figure 2: Fiale-2 injection rate and downhole pressure during the multi-rate injection test of the shallow reservoir.

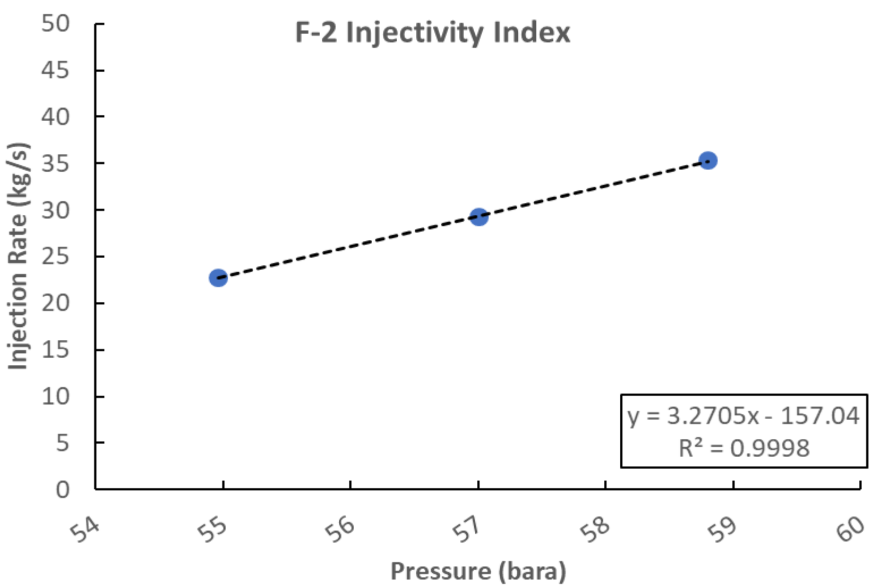

Figure 3: Injection rate and stabilized downhole pressure at 522.6 mMD during the Fiale-2 shallow injection test.

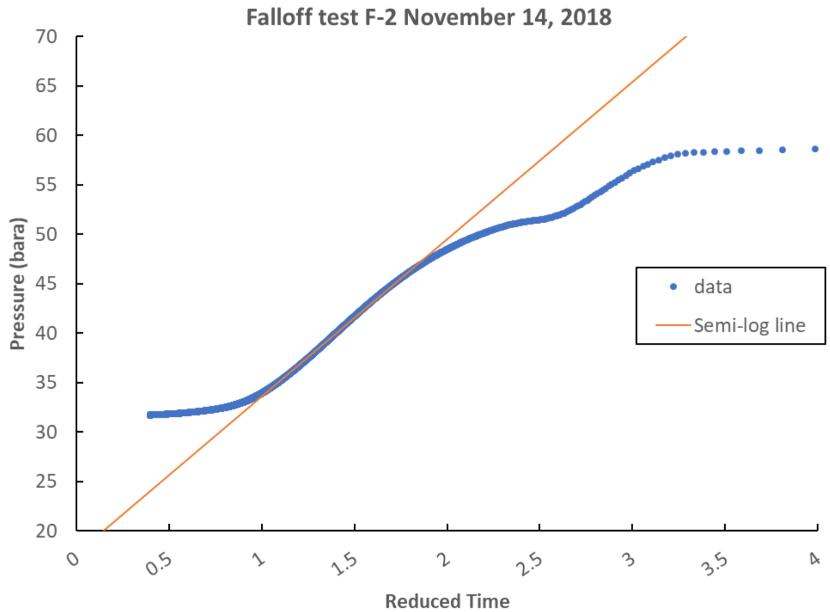

Figure 4: The semi-log plot of the measured downhole pressure during the Fiale-2 shallow reservoir PFO. The abscissa denotes reduced time (semi-log time).

The permeability thickness (kH) of the reservoir can be determined by:

$$1.15 \times \mathrm{Q} \times \frac{\mu}{2 \times \pi \times (\mathrm{m})} \div \delta = kH$$

where Q, μ, m, and δ are the final flow rate, dynamic viscosity, slope of latest straight-line segment of the semi-log plot, and conversion factor from m^3 to darcy-meter, respectively. With the parameters in Table 1, this calculation yields a permeability-thickness for the shallow reservoir of 2.85 darcy-meters. This permeability is within the range of permeability observed in commercial geothermal reservoirs.

Table 1: Parameters for kH of shallow reservoir based of the Fiale-2 shallow reservoir PFO test.

Parameter	unit	Value
Q	m^3/s	0.035
μ	kpa*s	7.10E-07
m	kpa/cycle	1633.6
2π	cycle	6.2832
δ	m^2/darcy	9.869E-13

2.1.2 Fiale-3 Shallow Reservoir

Two injection tests were completed to test the permeability of the shallow reservoir in Fiale-3. The initial Fiale-3 injection test evaluated the injectivity of the well between 552 and 743 mMD and the injectivity was determined to be very low (0.08 kg/s/bar). The second injection test was completed following a drilling break at 837 mMD with the well being open from 552 mMD to 845mMD. The stabilized downhole pressure data collected during the second shallow injection test with the tool set at 555 mMD and injection rates are summarized in Table 2.

Table 2: Injection rate and stabilized downhole pressure during the Fiale-3 shallow injection test.

Fiale-3 Shallow Injection Test	
Rate (kg/s)	**Pressure (bara)**
14.2	54.7
18.2	59.5
21.6	62.2

The injection rates and stabilized pressure indicate an II of 0.97 kg/s/bar. Apparently, the shallow zone in Fiale-3 has a moderate II, but likely has below commercial grade permeability based in this II.

Pressure fall-off data after the second shallow injection test were analyzed using (1) a multi-rate semi-log plot and (2) automatic inversion program DIAGNS (Mclaughlin, Barker, Owusu, & Garg, 1995). The multi-rate semi-log plot is exhibited in Figure 5.

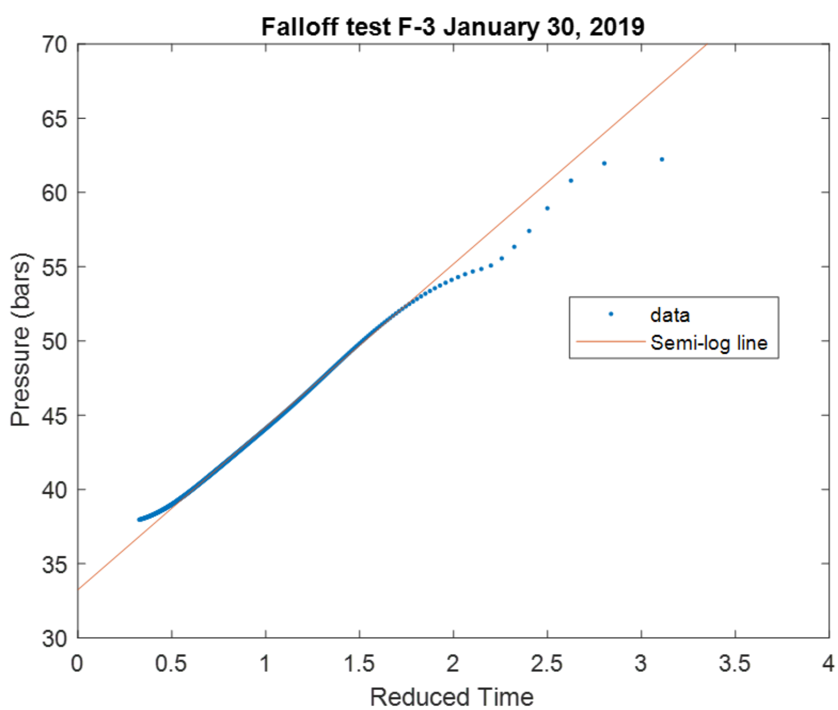

Figure 5: The semi-log plot of the measured downhole pressure during the Fiale-3 shallow reservoir PFO. The abscissa denotes reduced time (semi-log time).

The permeability thickness given by the parameters in Table 3 is 0.66 darcy-meter.

Table 3: Parameters for the permeability thickness of shallow reservoir based of the Fiale-3 PFO test.

Parameter	**unit**	**Value**
Q	m^3/s	0.023
μ	kpa*s	1.68E-07
m	kpa/cycle	1097
2π	cycle	6.2832
δ	m^2/darcy	9.869E-13

The classical finite-line source solution was used in DIAGNS to invert the pressure and flow data to obtain the formation parameters. Pressure data prior to 15:30 hours (30 min before stopping injection) were not included in the inversion because of a change in injectivity during the injection phase. Results are shown in Figure 6 and Table 4. Well Fiale-3 has a large negative skin (Table 4); indicating the well is highly stimulated. The transmissivity value (0.74 darcy-meters) is close to that obtained from the multi-rate semi-log plot (0.66 darcy-meter) (Figure 5).

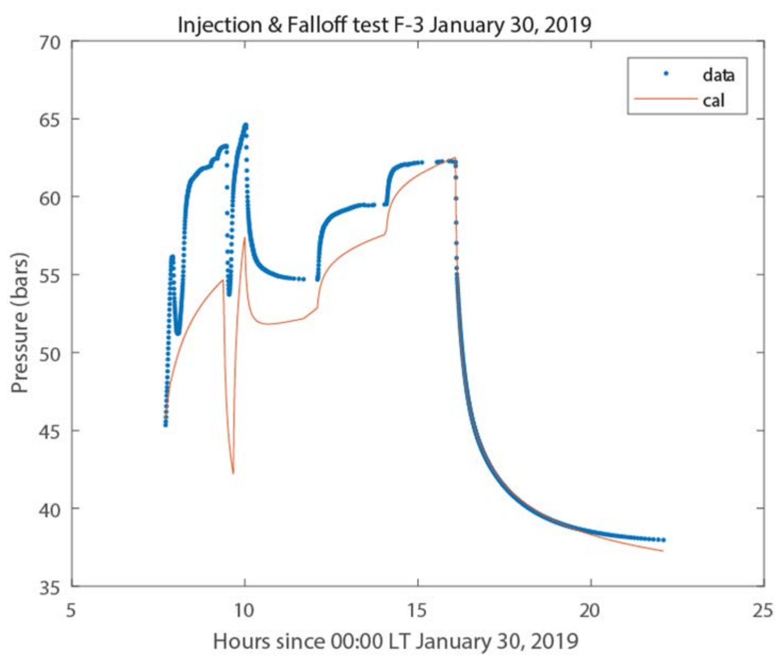

Figure 6: Comparison of computed pressures with measured pressures in well Fiale-3. The abscissa denotes time in hours since 00:00 LT January 30, 2019. Pressure data prior to 15.5 hours were not included in the inversion because of a change in injectivity during the injection phase.

Table 4: Parameters used for the calculation of Fiale-3 permeability-thickness in darcy-m based on PFO test after the second injection test of the shallow reservoir on 30-31 January 2019.

Parameter	Units	Value
Initial Pressure	bara	34.00
Transmissivity	Darcy-m	0.74
Storage Coefficient	m/Pa	6.68e-9**
Skin factor	Dimensionless	-4.09
Wellbore storage	Cubic m/Pa	2.31e-6
Pressure range	bar	26.65
Standard error	bar	0.242
Standard error/Pressure range	bar	0.0091

**Assumed to be 10 m x liquid compressibility at 162 ^{o}C.

2.2 Deep Injection Tests

2.2.1 Fiale-2 Deep Reservoir

A multi-rate injection and PFO test was conducted on 22-23 December 2018 to test the permeability of the deep reservoir when Fiale-2 was drilled to TD. The production casing is set to 2074 mMD, and production liner is set to 2455 mMD; the well is presumably open to formation between 2074 mMD to 2705 mMD. The downhole pressure data and injection rates for the injection test are shown in Table 5.

Table 5: Fiale-2 injection rate and stabilized downhole pressure during the deep reservoir injection test on 22-23 December 2018 at a depth of 2440 mMD.

Fiale-2 Deep Injection Test	
Rate (kg/s)	**Pressure (bara)**
27.7	222.3
9.5	212.8
3.6	211.0

The injection rates and stabilized pressure indicate an II of 2.1 kg/s/bar. These results are preliminary and the final injectivity may differ for several reasons.

1. The straight line fit to the data in Table 5 is relatively poor indicating unstable conditions during the test.
2. The pressure data was collected at 2440 mMD (just inside the liner), but it is likely that the main feedzone(s) is at least 100-200 m below this depth; the exact depth cannot be determined from the currently available data.
3. This test was completed using cold injection of seawater for a short period of time and the well was still cooling throughout the test. The pressure decreases during the test at the

wellhead and at 2440 mMD were primarily related to the cooling of the wellbore but could also be related to increasing injectivity since only 6 wellbore volumes were injected over the period of measurement.

4. The change in pressure at 2440 mMD was less than the change in pressure at the wellhead and the change in pressure at the deeper feed zone is likely to be less than the change in pressure at 2440 mMD, therefore, the II at the feed zone is likely to be higher, 3<II<4 kg/s/bar.

Production or injection of the well for some time (5-7 days) to remove drilling mud and cuttings and better establish equilibrium conditions will likely yield a determination the well's productivity and injectivity. These preliminary results suggest it may be a commercially viable well. A pressure fall-off analysis was not possible due to tool malfunction that resulted in the loss of data after the final injection period. Data loss was likely the result of battery failure due to the high temperatures.

2.2.2 Fiale-3 Deep Reservoir

A multi-rate injection and PFO test was conduct on 26-27 February 2019 to test the permeability of the deep reservoir when Fiale-3 was at TD. The production casing is set to 1730 mMD, and production liner is set to the TD at 2660 mMD; the well is presumably open to formation between 1730 mMD to 2660 mMD. The downhole pressure data collected are summarized in Table 6. The injection rates and stabilized pressure indicate an II of 0.50 kg/s/bar. This implies that the well currently has some but relatively low (sub-commercial) permeability.

Table 6: Fiale-3 injection rate and stabilized downhole pressure during the deep reservoir injection test on 26-27 February 2019 at a depth of 2200 mMD.

Fiale-3 Deep Injection Test	
Rate (kg/s)	**Pressure (bara)**
14.9	227.2
20.0	239.0
26.8	250.8

After the injectivity test, the well was shut-in and the pressure was measured at 2200 mMD. Pressure data obtained on 27 February 2019 were analyzed using (1) a multi-rate semi-log plot of the fall-off data, and (2) automatic inversion program DIAGNS. The permeability thickness given by the multi-rate semi-log plot is 0.22 darcy-meter. Two different mathematical models, classical line-source and composite reservoir, were used in DIAGNS to invert the pressure and flow data to obtain the formation parameters. For the line-source model, pressure data obtained after 40 hours were not included in the inversion since it proved impossible to match the entire fall-off data with the unbounded line-source model. Results are shown in Figure 7 and Table 7. It is clear from Figure 7 that the composite-model yields an excellent fit to the entire pressure data. Well Fiale-3 has a large negative skin (Table 7); indicating the well is highly stimulated. The formation in the vicinity of Fiale-3 has a rather low transmissivity of about 0.27 darcy-meter, which is close to that obtained from the multi-rate semi-log plot (0.22 darcy-meter). The composite model indicates that the formation at some distance (about 50 m) from the wellbore has a large permeability-thickness; thus, it may be worthwhile to attempt to stimulate F-3 by long-term injection and/or hydraulic fracturing to increase the permeability of the formation near the well.

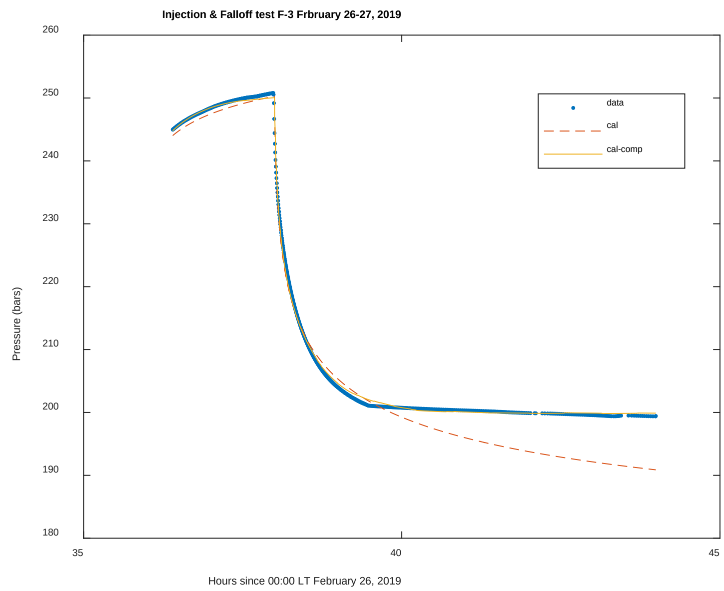

Figure 7: Comparison of computed pressures with measured pressures in well Fiale-3. The abscissa denotes time in hours since 00:00 LT February 26, 2019. Pressure data after 40 hours were not included in the classical finite line-source solution (cal) since it proved impossible to match the entire fall-off data with the unbounded line-source model. All the pressure data were used in the composite model (cal-comp).

Table 7: Formation parameters inferred from analysis of PFO data, January 30, 2019.

Parameter	**Unit**	**Finite-line Source**	**Composite reservoir**
Initial Pressure	bara	177.53	199.87
Transmissivity zone 1	Darcy-m	0.27	0.27
Storage Coefficient zone 1	m/Pa	1.23e-8**	1.23e-8**
Skin factor	dimensionless	-3.71	-3.67
Wellbore storage	Cubic m/Pa	2.31e-6	1.29e-6
Radius of discontinuity	m	Not Applicable	49.8
Transmissivity zone 2	Darcy-m	Not Applicable	Very Large
Storage Coefficient zone 2	m/Pa	Not Applicable	1.23e-8**
Pressure range	bar	51.42	51.42
Standard error	bar	1.05	0.585
Standard error	bar	0.020	0.011

**Assumed to be 10 m x liquid compressibility at 280 ^{o}C.

2.3 Pressure, Temperature, and Spinner Surveys

2.3.1 Fiale-3

One static PT survey of Fiale-3 was completed during each of the two shallow injection tests and two were completed during the deep injection test. The deep injection test additionally had two dynamic PTS surveys completed, one at an injection rate of 14.9 kg/s and one at a rate of 26.8 kg/s. Spinner data collected at the highest injection rate when the tool was moving up are plotted to show changes in fluid velocity more clearly. A static survey after 45 days of shut in is assumed to reasonably reflect formation equilibrium temperatures. PTS surveys and other well data are presented in Figure 8.

The initial static PT survey completed in Fiale-3 after the first shallow injection test indicates little permeability in the shallow reservoir up to 743 mMD. This is consistent with the injectivity test. The static PT survey completed after the second shallow injection test in Fiale-3 indicates a reversal in the deeper portion of the survey; however, this also corresponds to the region of increased permeability from the injectivity tests. Shut in temperatures in the portion of the well that was open at the time of the test appear to be 137-214°C, although the zones cooled during the injection test (~825 mMD) were still heating up at the time of the survey. A temperature reversal exists below 700 mMD.

For the deep injection testing, the 26 February 2019 dynamic survey and the 28 February 2019 static heat up survey (20 hours after shut in), a maximum temperature of 272 °C was measured at the total depth of the well (2640 mMD). Using the Horner build-up method, the rate of temperature increase between static surveys completed 6 and 20 hours after shut in was used to estimate equilibrium temperatures of 295-336°C in the section of the well open to production. This is in reasonable agreement with the temperatures measured after 45 days of shut in (281-362 °C).

The Fiale-3 temperature profiles clearly show the shallow reservoir (~500-850 mMD), the intermediate cold zone (~1000-1500 mMD), and the deep reservoir (below ~1700 mMD), as observed in all deep wells in the vicinity. The intermediate cold zone is sealed behind the casing in Fiale-3. Spinner data indicates fluid loss at depths of 2100 mMD, 2350 mMD, and 2580 mMD. Temperature data indicates fluid loss at 2350 mMD, and 2580 mMD. Based on both data sets, it appears that the most permeability occurs at 2350 mMD, and minor amounts occur at 2050 mMD and 2580 mMD. Equilibrium temperature at the main zone of permeability (2350 mMD) based on the Horner build-up method is 312 °C, measured temperatures at that depth after 45 days of shut in is 341 °C.

2.3.2 Fiale-2

Several static pressure-temperature (PT) survey of Fiale-2 were completed during the shallow injection tests and 28 and 105 days after the deep injection test. The deep injection test additionally had one dynamic survey completed. These surveys measured maximum temperature of 182°C in the shallow reservoir and 355°C in the deep reservoir. Permeability in the shallow reservoir was indicated at ~538 mMD, 681 mMD, and 750 mMD, indicated by relative cold zones which accepted water during injection testing and drilling.

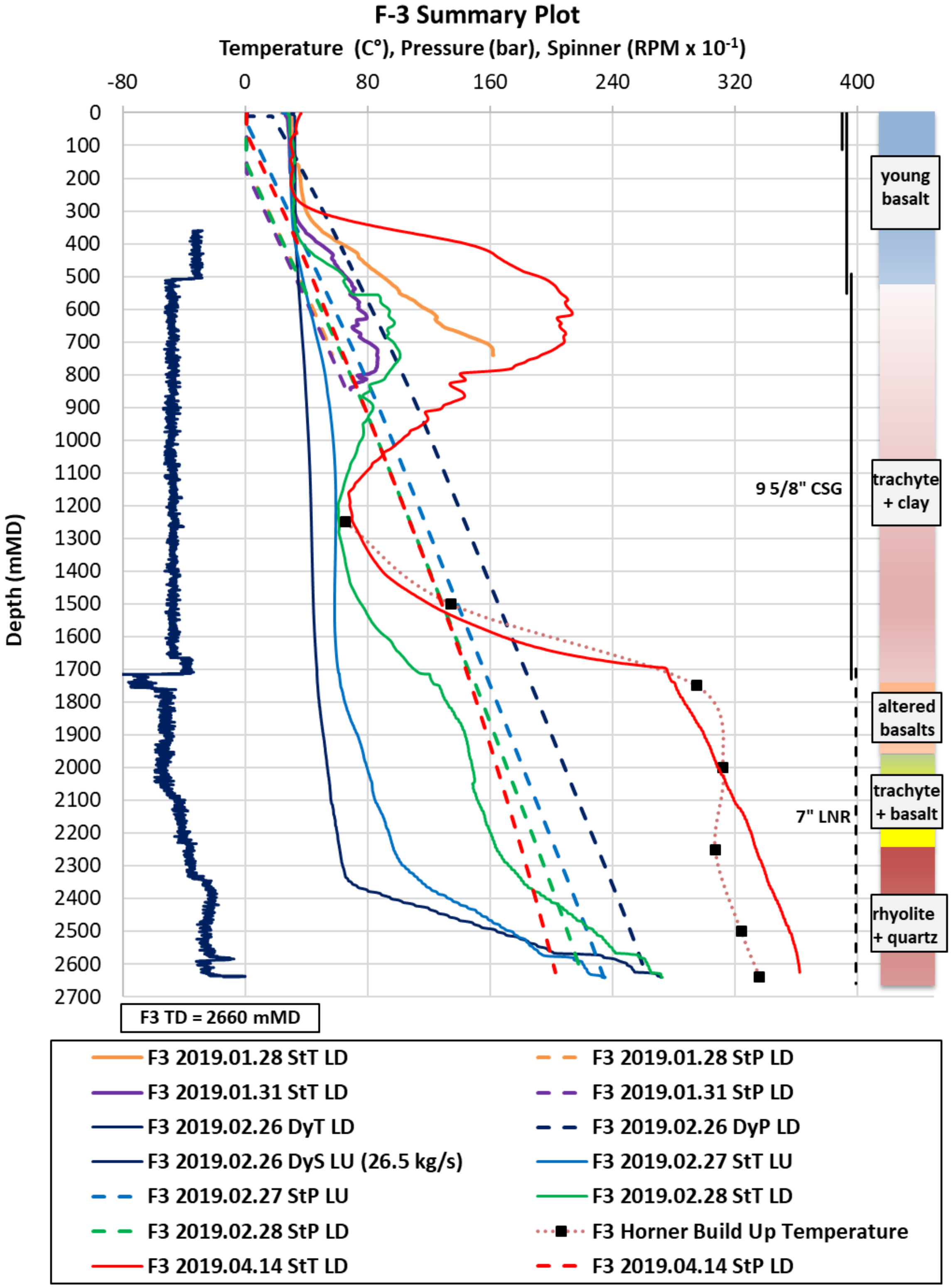

Figure 8. Fiale-3 summary plot showing selected PT surveys, well construction, generalized lithology, and Horner build-up temperatures. Legend displays the well (F3), date, well status (static: St, dynamic: Dy, data type (pressure, temperature, or spinner: P, T, or S), and survey direction (log up: LU, log down: LD).

Permeability in the deep reservoir was indicated at 2296 mMD and from 2390-2455 mMD. The temperature survey did not extend past 2455 mMD, and it is likely that the main permeability of the well is below this point as the temperature profile is isothermal in the lowest portion of the survey.

3. Conclusion

In summary, the completion testing in wells Fiale-2 and Fiale-3 was used to characterize both the shallow and deep geothermal reservoirs in the vicinity of the Fiale caldera. These tests confirmed the presence of commercially viable temperatures and permeability in the shallow and deep reservoirs. Shallow injection testing conducted during temporary drilling stoppages, in both Fiale-2 and Fiale-3 confirmed the presence of a potentially commercial grade shallow reservoir ultimately placed behind casing in these exploration wells. The data collected from these tests provides valuable input for the understanding of the geothermal systems in Fiale caldera and can be used in future development planning targeting the shallow reservoir. The testing of Fiale-2 yielded valuable information that was employed to inform the drilling location, target, and well construction of Fiale-3. This information successfully aided in the planning on Fiale-3 as the well (1) seals out the intermediate cold water intrusion, (2) the production liner begins at the top of the high temperature deep geothermal resource, (3) the well encountered some permeability (II=0.50 kg/s/bar, kH=0.27 darcy-meter) and testing suggests greater permeability may exist at some distance from the wellbore and the productivity of the well may be increased through stimulation. Deep injection testing conducted as part of completion testing in both Fiale-2 and Fiale-3 indicates the possible presence of a commercially viable deep resource, prior to the completion of more costly and involved production testing activities.

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